A Comprehensive Infrastructure and Methodology for Multi-Modal Data Acquisition to Empower AI-based Rehabilitation

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Limitations Affecting Real-World AI Rehabilitation Systems

Why do AI-based rehabilitation systems struggle transitioning from research environments to clinical practice?

- ✓ Unstable sensor synchronization
- ✓ Drift and anatomical misalignment
- ✓ Inconsistent exercise labeling
- ✓ Poor dataset reproducibility

Reliable AI requires reliable, synchronized and anatomically consistent data.

Bridging Accuracy and Real-World Deployability

Optical Systems

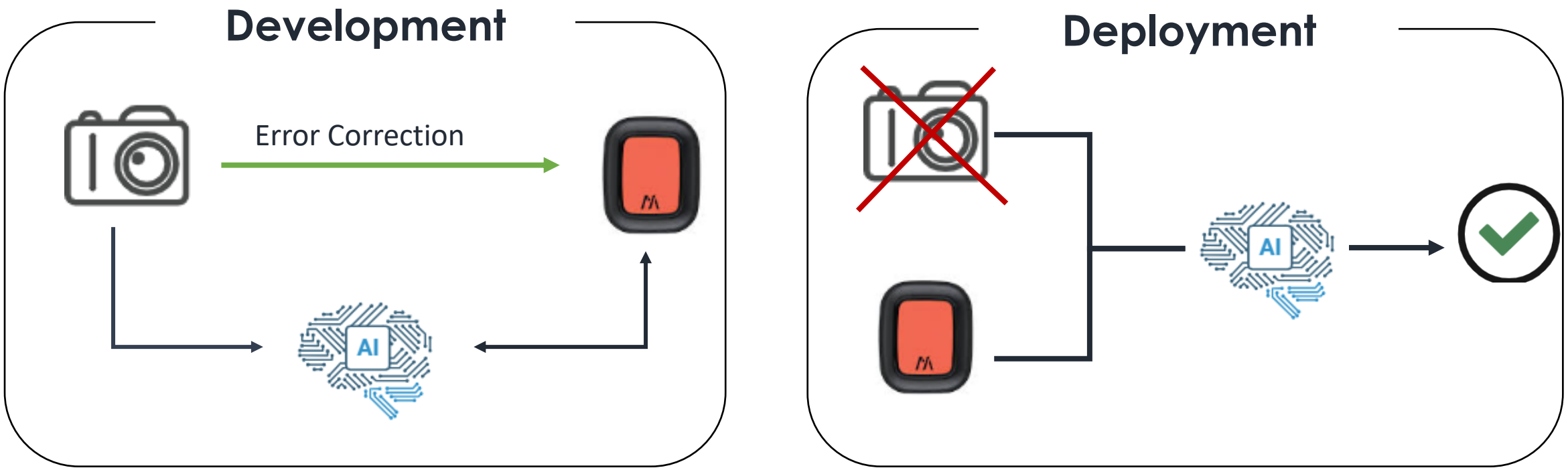
- High spatiotemporal precision
- Laboratory controlled environment
- Limited scalability for home use

Wearable sensors (IMUs)

- Real world deployable sensing
- Cost effective and portable
- Susceptive to drift and alignment errors

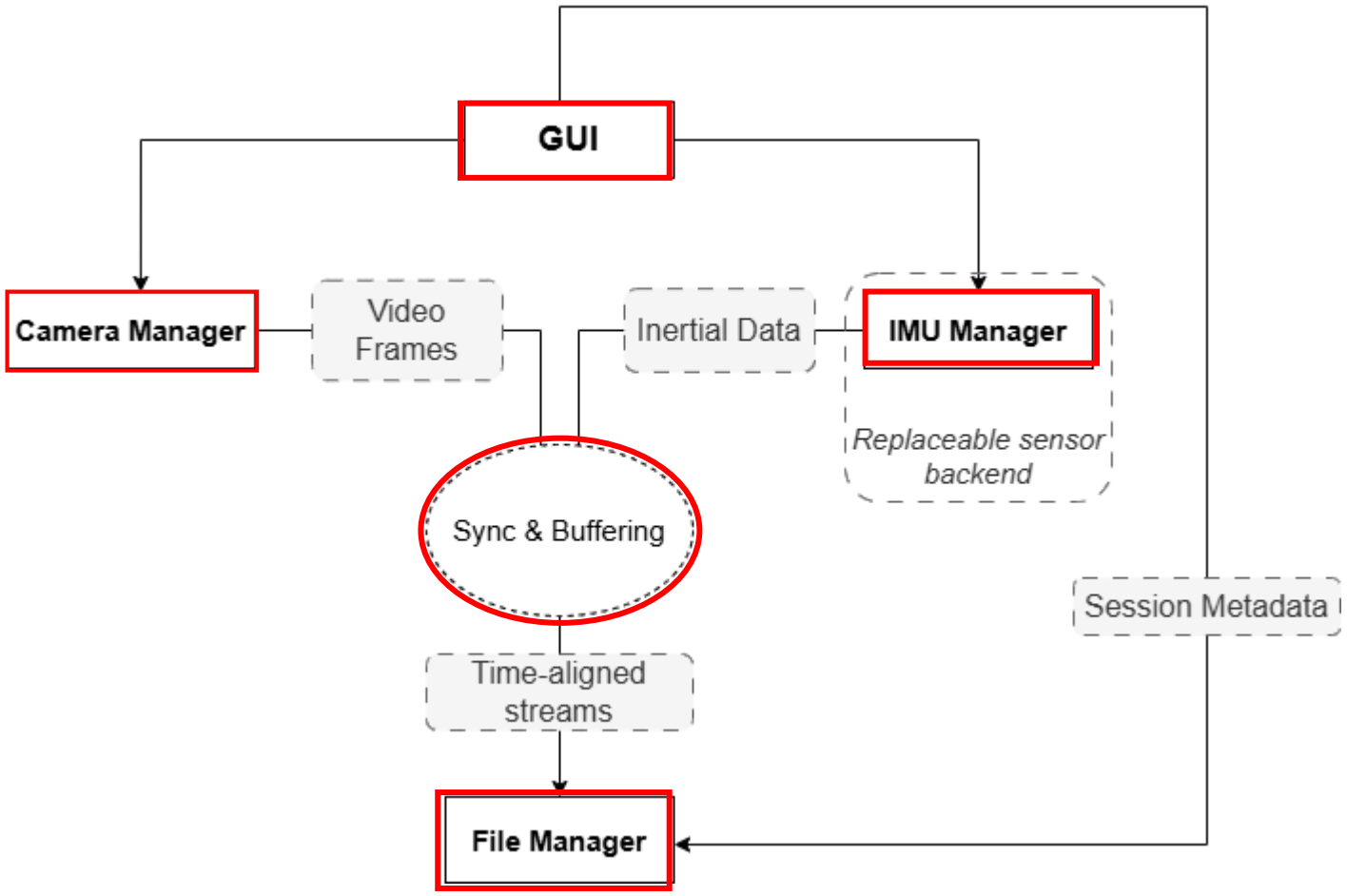
Multimodal synchronization bridges accuracy and scalability

From Multimodal Supervision to Sensor-Only Development



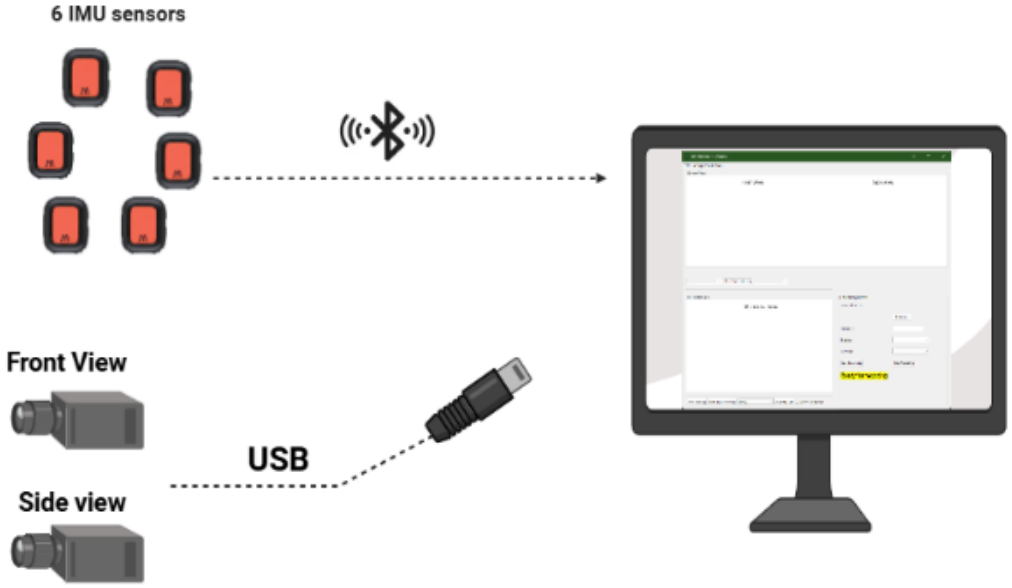
Multi-modal data collection is the bridge to reliable AI models for unsupervised recovery.

Recording Studio – System Architecture



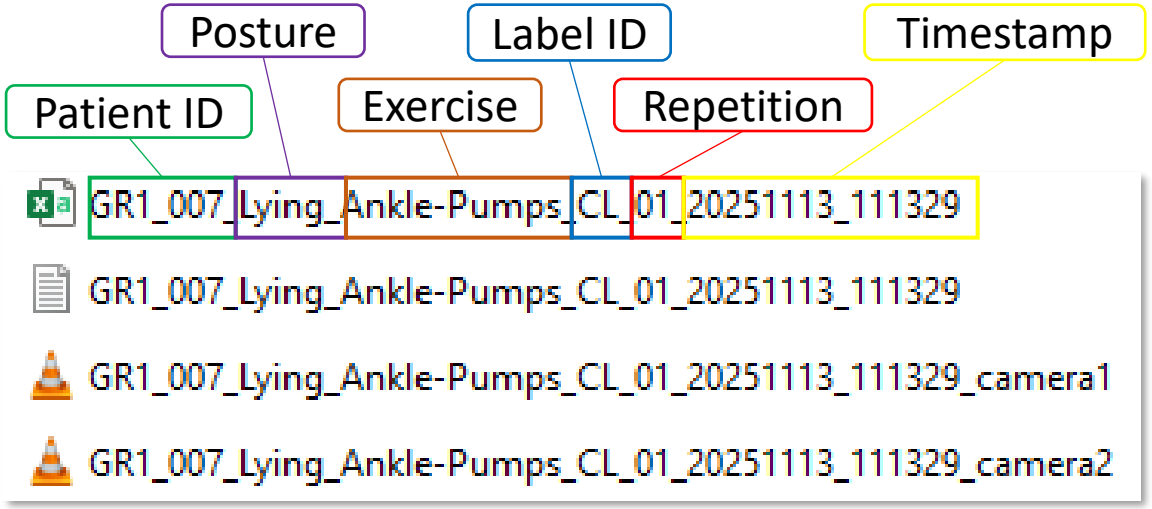
- ✓ **Centralized Control Layer**
  GUI-based configuration and session management
- ✓ **Concurrent Multi-stream Acquisition**
  Event driven concurrent multi-stream acquisition
- ✓ **Time aligned Dataset generation**
  Buffered synchronization before storage
- ✓ **Replaceable Sensor Backend**
  IMU Manager can be adapted to different wearable devices

Recording Studio - Multimodal Recording and Data Export



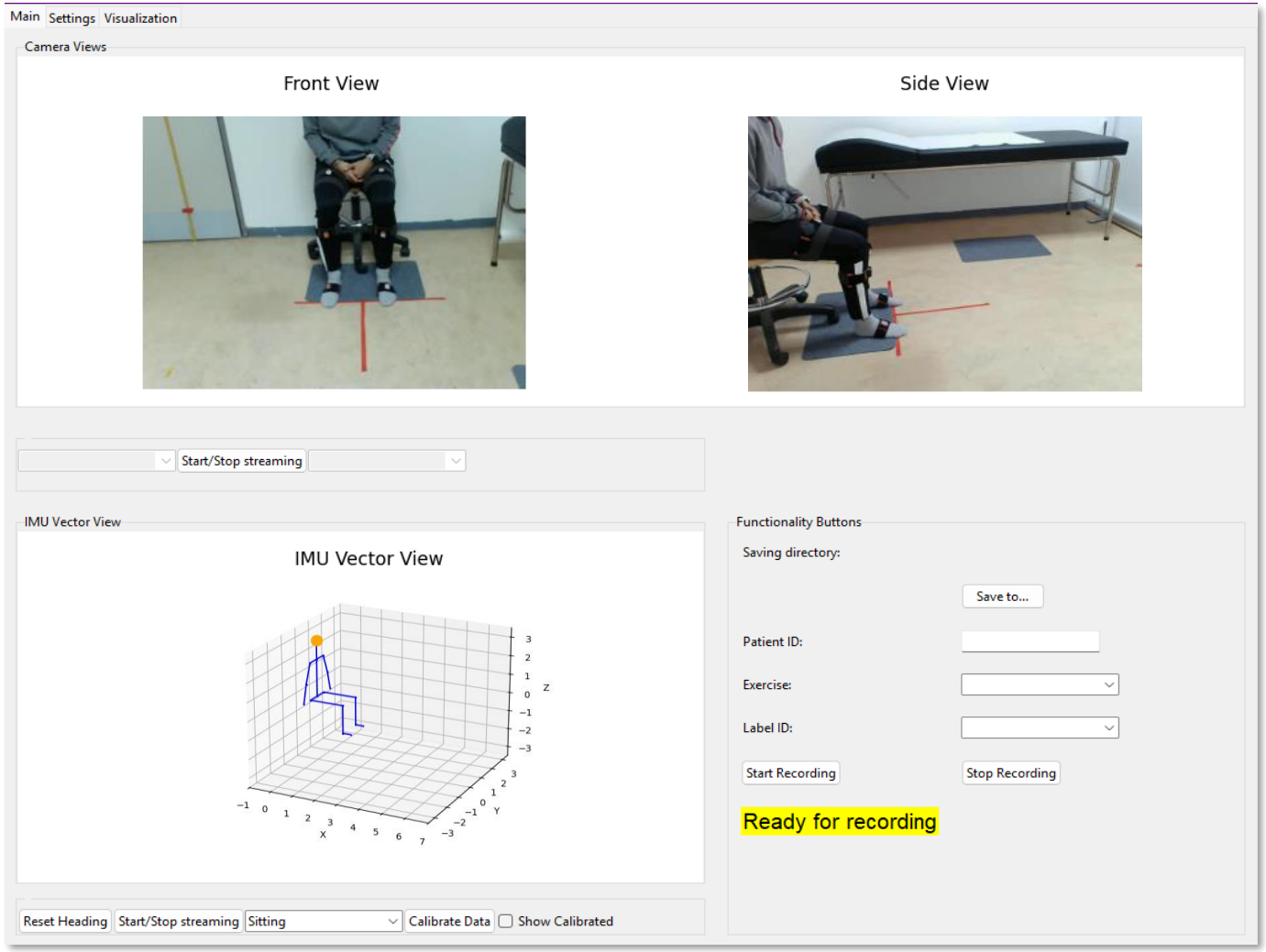
- Six Movella DOTs concurrent BLE streaming with synchronized inertial timestamps.
- Frontal and lateral optical recording for multimodal supervision.

- Frame - rate alignment:
  30 Hz inertial sampling & 30 fps video capture.
- Structured dataset export:
  IMU data (.csv and .txt format) and
  dual-camera recordings (.mp4 format)



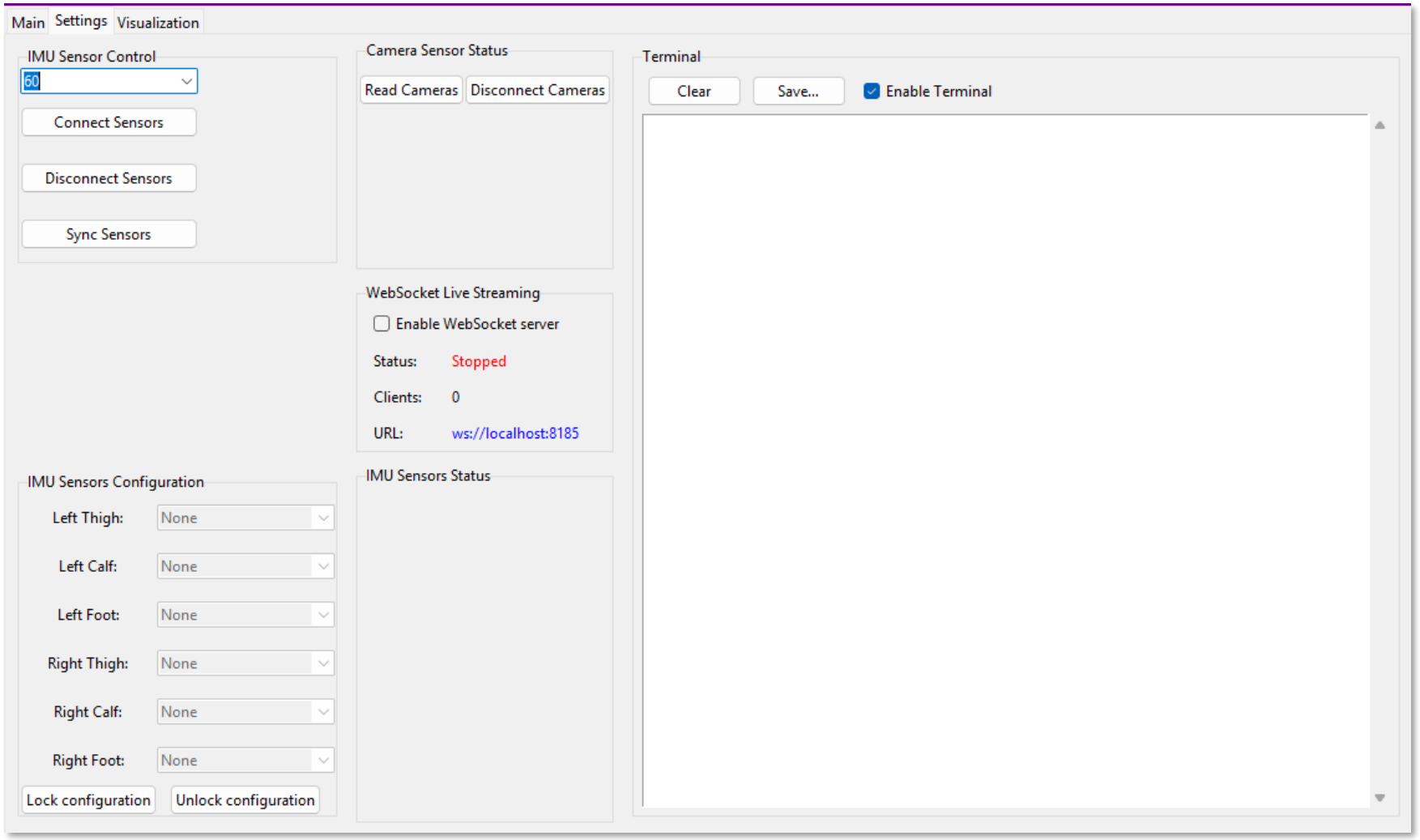
Integrated Control and Visualization Environment

Main Tab



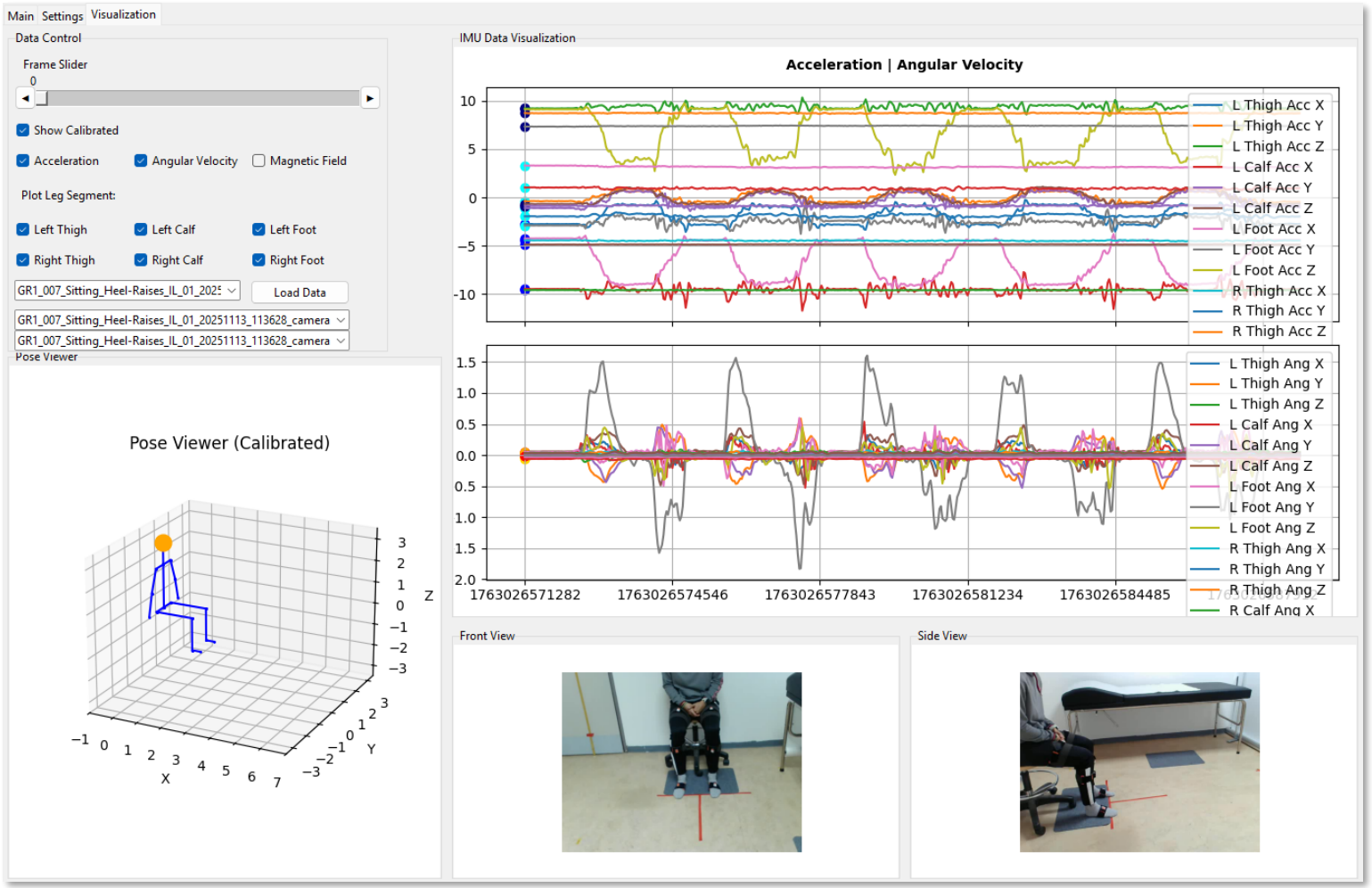
Integrated Control and Visualization Environment

Settings Tab

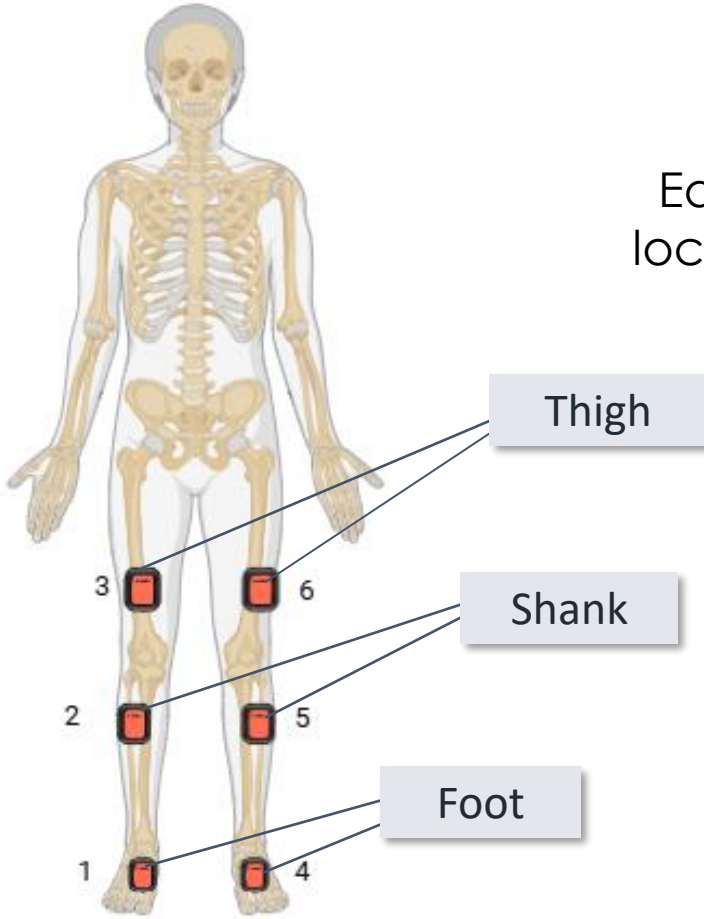


Integrated Control and Visualization Environment

Visualization Tab



Sensor Placement and Coordinate System Mapping

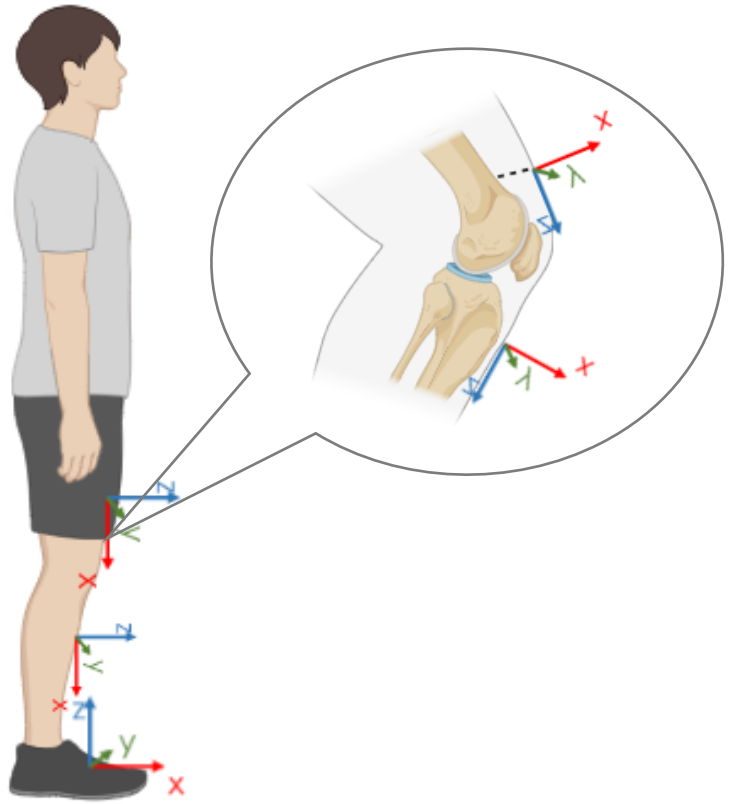


Thigh

Shank

Foot

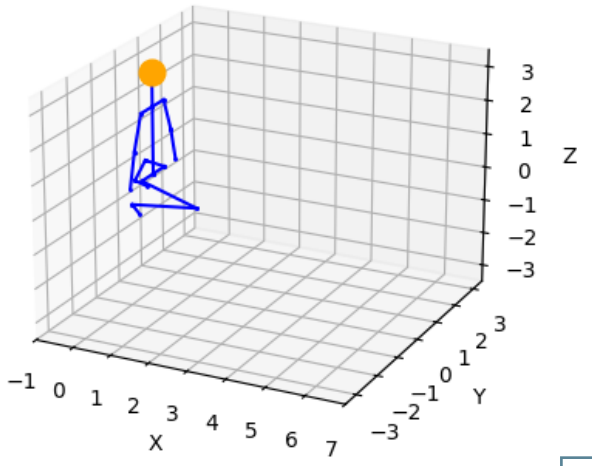
Each IMU reports signals in its local coordinate system (X-Y-Z)



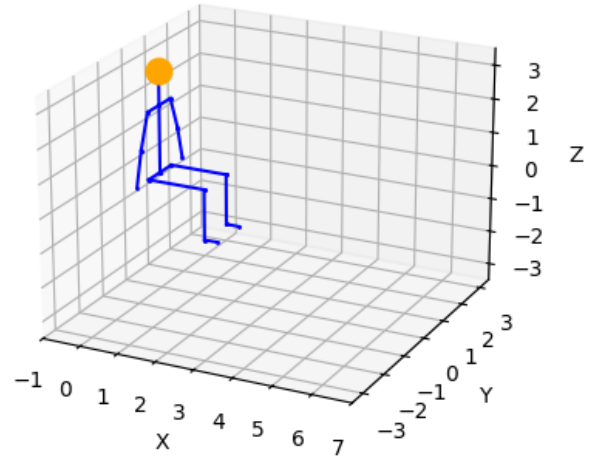
Reliable kinematic estimation requires consistent sensor-to-segment alignment across all local coordinate systems.

Static calibration for Anatomically Consistent 3D Pose

Before (Uncalibrated)



After (Calibrated)



$$q' = q_{calib}^{-1} * q$$

Static Calibration: aligns local sensor frames to anatomical segment references through quaternion normalization.

Temporal Consistency Across Six IMUs

33.4 ± 0.5 ms

Mean sampling interval
N≈6,000

<0.004%

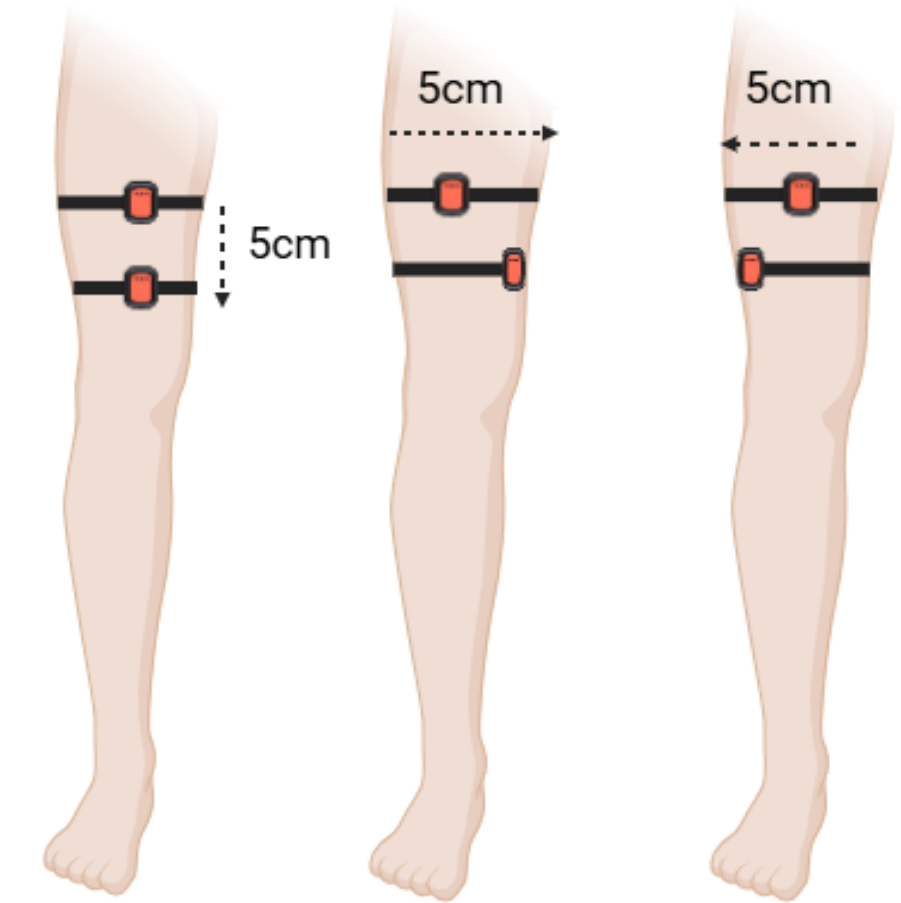
Packet Loss

29.9 ± 0.2 Hz

Experimental Frame Rate
(Target: 30Hz)

Stable concurrent BLE streaming under multimodal acquisition conditions.

Impact of Sensor Misplacement on Acceleration



Vertical Misplacement (5cm) ↓

RMSE X: 0.045 ± 0.025 g *(static gravitational component)*
RMSE Y: 0.039 ± 0.020 g
RMSE Z: 0.10 ± 0.06 g
PAE Z: 0.2608 g

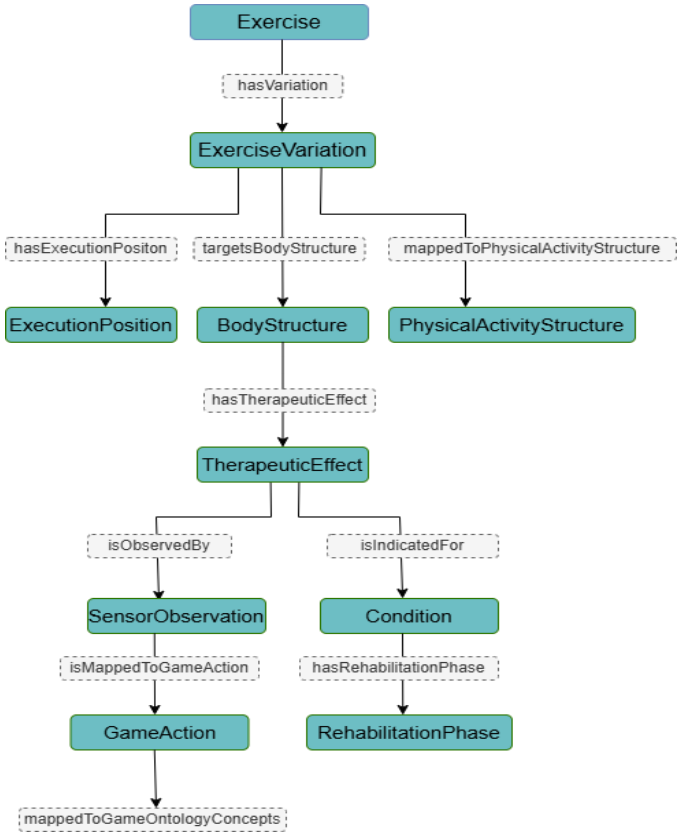
Inward Lateral Misplacement (5cm) ←

RMSE X: 0.104 ± 0.083 g
RMSE Y: 0.0055 ± 0.090 g
RMSE Z: 0.243 ± 0.307 g
PAE Z: 0.938 g

Outward Lateral Misplacement (5cm) →

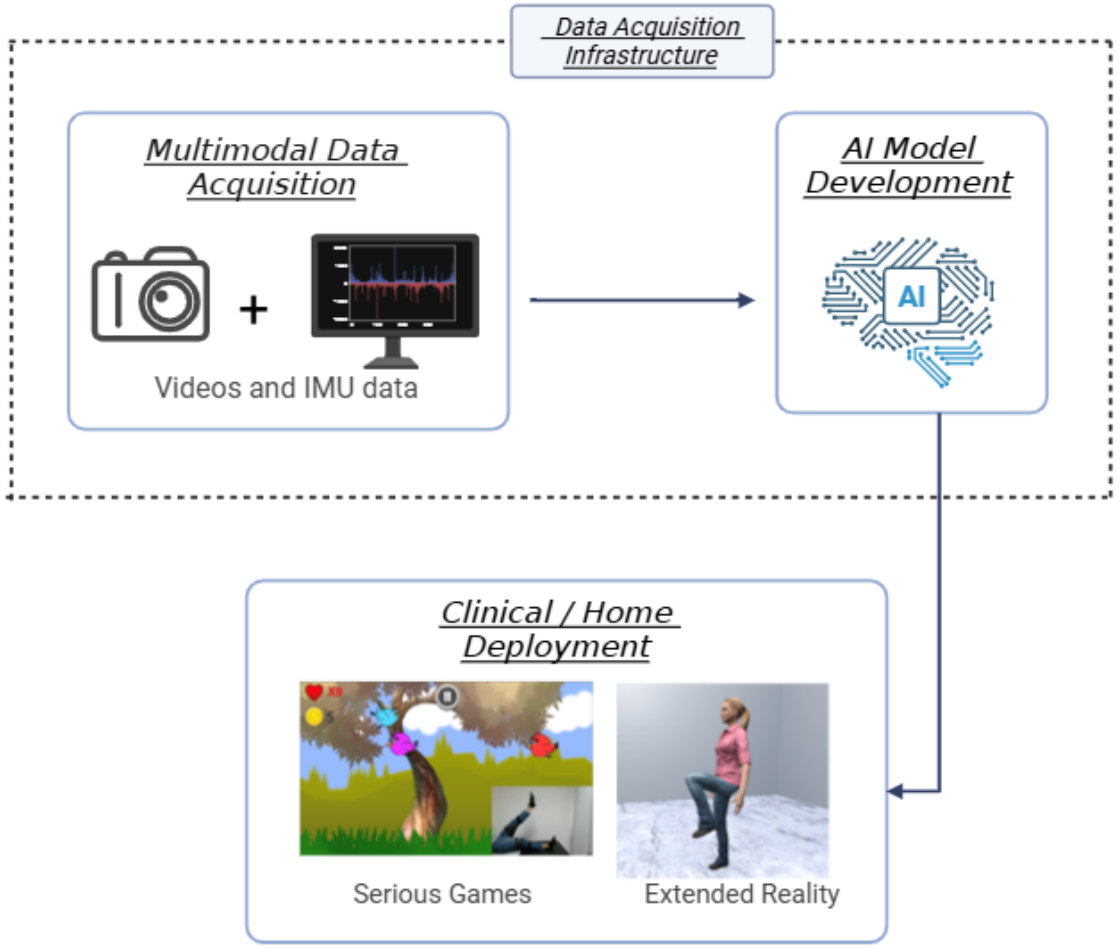
RMSE X: 0.0735 ± 0.057 g
RMSE Y: 0.079 ± 0.148 g
RMSE Z: 0.131 ± 0.140 g
PAE Z: 0.505 g

Towards an Ontology based Data Structuring



- ✓ Formal definition of exercises and variations.
- ✓ Explicit mapping of anatomical segments and sensor positions.
- ✓ Structured linkage between segment movements and game actions.
- ✓ Alignment with clinical standards (e.g., PACO, ICF, SNOMED CT, ICD-11).

Towards an AI-Enabled Deployment



- ✓ Cross-modal synchronization validation
- ✓ Annotation & labeling
- ✓ AI model development for exercise classification

"The proposed infrastructure serves as the foundation for scalable, AI-enabled rehabilitation systems."

Thank you!

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